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The Use of Magnetoencephalography in Evaluating Human Performance

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Michael Drillings

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THE USE OF MAGNETOENCEPHALOGRAPHY IN EVALUATING HUMAN PERFORMANCE

CONTENTS

THE USE OF MAGNETOENCEPHALOGRAPHY IN EVALUATING HUMAN PERFORMANCE[1]

I. Introduction and Overview

The magnetoencephalography (MEG) program at Los Alamos has reached a number of milestones in its objectives of understanding neural aspects of human performance and contributing to improved human performance through proper selection of personnel for specialized positions or better training procedures. The basic equipment for obtaining sensitive measurements of the magnetic fields emitted from the brain during information processing tasks has been assembled and utilized. The necessary computer software and data acquisition hardware have been tested and a number of experiments performed. Experiments have localized neural processing activity for auditory, visual, and somatosensory modalities. The results have been very encouraging and have clearly shown the promise of MEG. They have also convinced experts in a variety of neuroscience fields of the value of this technique for studies of neural processing of complex information.

The general goal of this program available from Army Research Institute (ARI) has been to see if MEG can aid in the selection and evaluation of personnel and/or the evaluation of training. We have begun cognitive experiments, which already show promising pilot data, to indicate whether individuals with high spatial discrimination skills (e.g., radar operators, marksmen, tank drivers) can be singled out based on their brain characteristics alone. This exciting potential could allow preliminary screening of military

[1] Funds for this program were made available from the Army Research Institute.

personnel at an early or advanced level, depending on the difficulty of the assignment.

Also being developed are stress examinations based on MEG results that might be able to indicate an individual's tolerance for stress both on a day-by-day basis or relative to other individuals. These and other advanced cognitive paradigms are based on a thorough scientific analysis of MEG experiments using simple stimuli. Thus, the underlying neural sources involved in MEG-evoked response studies are well characterized before the more complex responses from higher cognitive processes are examined. In this process, no important scientific steps are skipped.

Of equal importance to the experimental progress is the technological progress. If the advanced cognitive paradigms now under study are to be used for a large number of individuals and if the results are to be evaluated rapidly, considerable progress has to be made on technological issues. Results obtained at Los Alamos on these issues are quite encouraging. For example, new algorithms to reduce the number of trials needed to obtain good signal-to-noise ratios (reducible to a single trial for sufficiently large sensor arrays in some cases) have been developed. This new development has significant implications for the general use of MEG and, in particular, for the study of persons engaged in tasks that test their intrinsic abilities.

Other developments on the accurate positioning of MEG sensors around the head are also very exciting. Time-consuming placement and manual measurement of dewar locations will no longer be necessary due to accurate positioning feedback coming from small coils located on a headband around the subject's head. This will provide much more rapid processing of individuals. New sensor

designs have also been initiated to provide improved neural source localization ability by using more compact sensor arrays. New, high-temperature superconducting SQUIDs now under development at LANL will provide a much more suitable device for use in the field. All of these developments represent the most significant technological innovations to date. There are a number of other developments also under way that will additionally enhance the use of MEG for the processing of large numbers of personnel.

The general strategy for the MEG experimental program has been to work in a hierarchical fashion, i.e., perform simple, easy-to-understand experiments first. This approach enables a better understanding of the data and of how the stages of information processing relate to each other. Thus the program to date has attempted to break down a complex task into more easily identifiable and manageable components, and then add complexity into the task, one step at a time. This theme is illustrated in our studies of basic auditory, visual, and sensorimotor processes. These studies were necessary for validating MEG as a viable technique and for understanding the component structure of the waveforms associated with pure sensory events. Then a behavioral response to a sensory response was added. By adding such parameters as reaction time to the paradigm, one now has a measure of speed (e.g., the composite reaction processes) and measures of accuracy.

II. Progress to Date

A. Visual Studies

1. Experiment 1

a. Rationale and method

Experiment 1 represents an integration between the retinotopic mapping

studies performed on monkeys (invasive, single-unit studies) and human psychophysical studies on detection of sinusoidal gratings presented in visual space. The purpose of this experiment is to validate MEG as a noninvasive technique for examining a range of neurophysiological functions. Evoked response paradigms allow one to examine the neural processing between the stimulus and the behavioral response. Standard cognitive tests cannot address such issues. It should be possible to resolve, both temporally and spatially, different levels of processing various kinds of information.

The general strategy used in the validation studies can be summarized as follows (see Figs. 1 and 2). Seven neuromagnetic waveforms are collected simultaneously while a stimulus is presented in various positions in the visual field. This procedure is repeated until at least 6 to 7 cortical locations are sampled (resulting in 42 to 49 different neuromagnetic waveforms collected over occipital and parietal cortex). The information contained in the 42 to 49 neuromagnetic waveforms can then be summarized by selecting critical points in time (e.g., 100 ms poststimulus, which is a peak in the MEG waveform) and plotting the field distributions (i.e., contour plots based on the amplitudes observed at each sensor location) for each of these time points. The field maps enable one to determine approximately where the source of the effect (i.e., current dipole) resides in a 2-D surface projection map. A least squares algorithm is then applied to the data to determine the coordinates (including depth and orientation) of a theoretical dipole that best fits the empirical field distribution (see Fig. 2). Contour maps of the forward solutions (the theoretical field distribution) and "goodness-of-fit" measures aid in determining whether the theoretical solution is reasonable. If the

solution is reasonable, the location of the source can be placed on the magnetic resonance imaging (MRI) scans. This represents a final step for this particular set of experiments--the placement of functional maps onto anatomical structures.

A brief description of the paradigm follows. If more detail is desired, please see the accompanying reprints and abstracts. Two spatial frequencies (1 and 5 cycles per degree (cpd) were presented either in the central visual field (CVF) or in the right visual field (RVF). In a few cases, the gratings were presented in the left visual field. Subjects were instructed to count and mentally classify each stimulus type. Neuromagnetic responses were monitored with a seven-channel SQUID-coupled gradiometer system. Sensors were located on a 2 cm equilateral triangular grid (i.e., the center and vertices of a regular hexagon).

b. Results and Discussion

We observed major differences in magnetic field distribution as a function of the visual field of stimulation. This observation was consistent with the single-unit studies on retinotopic mapping of visual cortex. Figure 3 shows how the distribution (and therefore, the location of the dipole) changes when the stimulus was placed 3 to 4^{o} in a lower left quadrant, 3 to 4^{o} in the lower right quadrant of the central field, and 7 to 8^{o} in the right field. Consistent with human psychophysical studies, there was also a statistical interaction between field stimulated and spatial frequency (1 or 5 cpd). Greater amplitudes were noted to the 5 cpd grating when presented to the central field. In contrast, greater amplitude responses were noted to the 1 cpd grating presented in the periphery. This result is consistent with an

interpretation based on cell density in the retina. The central retina contains more cells with smaller diameters than peripheral retina and is more specialized for fine-grain resolution. Cells in the peripheral retina tend to be fewer and generally larger. Therefore, these cells respond best to lower spatial frequencies (e.g., 1 cpd) while the central retina responds best to higher spatial frequencies.

Figure 1 demonstrates that when we superimpose the functional map for the P100 (the arrow represents current flow) on an MRI scan, the source is to near the calcarine fissure (striate cortex). This step of the process has been performed for two subjects thus far. In the near future, we should be able to digitize the MRI scans in order to have a realistic 3-D anatomical map for each subject upon which we can superimpose a number of functional maps.

2. Experiment 2

a. Rationale and Method

In keeping with a general strategy of working from simple to more complex designs, the stimulus parameters of experiment 2 were identical to those in experiment 1. The only differences were as follows: 1) Subjects were instructed to attend to one stimulus condition during an entire trial block (e.g., attend to the 1 cpd grating in the RVF), and 2) to ensure that subjects were attending, they were required to give reaction-time (RT) responses to the attended stimulus. These differences allow us to examine changes in brain responses associated with higher-order tasks and allow us to correlate RTs (indexing speed of processing) and task accuracy (percentage of "hits" and "false alarms"), with the neural responses. Subjects were forced to respond

quickly (within 600 ms), otherwise the data from that trial was discarded and the trial was repeated.

b. Results and Discussions

Sensory Responses and RTs. Because the subjects were rquired to respond quickly, differences in onset and peak latencies in the MEG, associated with field of stimulation and spatial frequency, were more robust than in the previous study. However, we were surprised to see no correlation between the RT measures and early sensory activity (e.g., P100).

Figure 4 shows neuromagnetic responses at an extrema and corresponding RTs for two male subjects. Generally speaking, all four subjects showed similar trends in the RT data but all subjects showed unique patterns when the MEG responses were examined. Subject LD, for example, showed faster behavioral responses to the low spatial frequency (1 cpd) grating presented in the CVF, but LD showed an earlier peak latency in the MEG to the low spatial frequency (SF) grating presented in the RVF. Subject GM, however, showed primarily a visual field effect in the MEG waveforms. That is, information presented to the periphery was transmitted through the visual system more quickly than information presented in the CVF. Subject LD, on the other hand, showed an interaction between SF and field of stimulation. These results indicate that subjects do process visual information in different ways. We did not examine areas where sensorimotor integration would most likely occur. We might achieve better correlations between the behavioral and neuromagentic responses in this region. Also, one would expect better correlations between the MEG and RTs responses if one focused on the time-course of the attention effects per se. For example, subjects who show an earlier onset of effects associated with

attending a particular stimulus may show faster RTs. This has not yet been examined systematically.

Effects of Selective Attention. Figure 5 shows contour plots for two components of the MEG (P100 and P300) when a stimulus was attended vs not attended. Visual inspection of these contour maps shows the following results: 1) Attention appears to primarily modulate the amplitude of the sensory response; 2) the location of the current dipole does not change significantly between attended and nonattended conditions; and 3) there appear to be differences in source depth. Field extrema are further apart in the nonattended condition, which implies a deeper source. These results taken together suggest that visual spatial attention acts to enhance the sensory activity associated with processing the spatial stimulus. However, we cannot say at this time whether the observed changes in depth of the source are due to changes within the cortical layers themselves or due to a shift in the source along the calcarine fissure. It is probable that both of these events are happening.

Thus far we have focused on sensory and selective attention paradigms and have added a behavioral task that gives us information concerning the speed and accuracy of behavioral responses which we can correlate with the neural responses. The next step will be the administration of neuropsychological tests. We may be able to find correlations, between the neuropsychological tests and MEG responses, which are not evident when the neuropsychological test scores are compared with the RT data.

It appears that the processing of visual information is not as hard-wired as we tend to believe. We are surprised at the variability reflected in the

MEG responses. It is possible that these differences reflect both differences in cortical geometry and strategies employed. We feel that this finding represents a real strength of the MEG technique. As mentioned previously, a major advantage of an evoked response paradigm over standard cognitive tasks is that one can examine processing between the stimulus and the motor response (e.g., RT). Now we find that cortical geometry or anatomical differences may play a major role in how people "see" the world about them. Different cortical geometries may shape an individual's responses in a unique fashion. This is the kind of information that standard pencil and paper tests cannot directly address. In addition, MEG allows direct measurement of a subject's cognitive strategies during the performance of specific behavioral tasks. For example, given a constant level of behavioral output in two subjects, MEG may reveal fundamentally different neural responses, which reflect different levels of cognitive effort.

B. Auditory Studies

The long-term goal of this series of studies is to determine whether the spatio-temporal pattern of noninvasively recorded brain activities can be correlated with unique cognitive activities and performance capabilities. If we can isolate patterns of magnetic fluctuations that correspond to specific cognitive strategies, it may then be possible to reliably monitor a subject's ability to maintain optimal levels of performance.

The strategy we have employed is basically three-fold: First, we examined the pattern of activity associated with auditory stimuli of varying frequencies to assess the sensitivity of the neural measures to a changing sensory environment. This phase was completed in FY-86. Second, following the

identification of basic sensory organization, we examined the modulatory role of selective auditory attention on the sensory evoked responses. This second phase has been completed and forms the basis of this summary. Last, we will examine the effect of increasing levels of stress upon the decision making process. This final phase will be initiated in FY-88.

The data were collected from four right-handed subjects using a seven-channel neuromagnetometer. The field was measured at 21 to 35 points over the temporal regions of both sides of each subject's head. This was achieved by placing the probe sequentially over 3 to 5 locations on each hemisphere. The MEG was digitized for 150 ms prior to stimulus onset and continuously for another 600 ms poststimulus. Subsequently, these data were used to construct maps of isofield contours, and the underlying dipoles were then fit by equivalent current dipoles using a least squares code. In two subjects, the EEG was also recorded from Fz and Cz.

A dichotic listening paradigm was employed in which standard tone bursts (1000 and 500 Hz) were presented with overall probabilities of 40% each. The frequency presented to each ear and the ear attended was counterbalanced across stimulus blocks. The subject's task was to respond to occasional target tones in the attended channels (probability 10%) that were identical in frequency to the standard tones in that ear, but longer in duration. Eight counterbalanced blocks were presented at each MEG scalp location, with a break in the middle.

Figure 6 shows simultaneously measured magnetic and electric responses from two subjects. It can be seen that the magnetic and electric responses are quite similar in waveshape. In the electrical records, both attended and ignored stimuli elicited a negative deflection at about 100 ms (N1). Magnetic

responses showed a prominent deflection at about the same latency (N1m). However, the waveform of the event-related field (ERF) is very sensitive to the position of the sensor: magnetic fields recorded from the two ends of the auditory cortex show an inversion in the direction of current flux so that the peak amplitudes are of opposite magnitude when recorded from the anterior and posterior positions. In the convention used here, a positive deflection represents magnetic flux into the head and a negative deflection represents outward flux. The long duration difference between the attended and the unattended channels seen in Fig. 6 corresponds to the Nd in the electric recording and the Ndm attention related auditory magnetic fields.

Ndm of the MEG. Figure 7 shows a simultaneous seven sensor recording measured near the "zero crossing" region of the N1m component for one subject. The waveforms represent the attended and unattended response to a 1KHz tone presented to the left ear. Sensor locations 1 through 7 are indicated in the upper left corner of each waveform. The x,y values indicated in parentheses beneath the sensor number are in centimeters with respect to the left periauricular point. Positive x values are anterior to the periauricular point. The vertical dashed lines on waveforms recorded at sensors 1, 3, and 6 indicate approximately 100 ms and 200 ms following stimulus onset. These data clearly show the separation of sources for the N1m and P2m components. While the N1m component reverses in polarity between sensors 3 and 6, the same is not true for the P2m. The turnover point of the P2m component is at some point anterior to the measured positions of this figure.

Figure 7 also indicates that the source of the Ndm component associated with selective attention is distinct from the N1m source. Note that the

attention related waveform between 200 ms and 500 ms post stimulus has a positive magnitude with respect to the ignored channel at all sensor locations, including sensors 6 and 7, where the N1m component has reversed polarity. Since the polarity of the N1m has changed at these locations, but the Ndm deflection has not, the sources must be separate.

A final provocative feature of Fig. 7 occurs for the N1m component. While there is no difference in amplitude between the attend and the ignored response at sensor 3, there are differences at every other location. The N1m response to the ignored stimulus appears to have a different crossover compared to the attended N1m response. For example, the response at sensor 7 shows a clearly inverted N1m component for the ignored stimulus, but the response to the attended ear stimulus is still at baseline amplitude. Therefore these data suggest that there may be a different source of N1m activity recruited under the condition of selective attention that is not present when the stimulus is ignored. A manuscript describing this experiment in detail is in preparation.

In summary, our auditory studies have demonstrated that the earliest component of the evoked response (prior to 100 ms), is affected by the stimulus frequency, but remains insensitive to attentional states. The subsequent N1m component is not frequency dependent, and can be modulated by attention, probably through a gain control mechanism. Finally, the later Ndm component reflects a unique neural process which is tightly coupled to behavioral relevance. It will be of particular interest in our next phase of study to determine whether this "endogenous" process will also reflect the effect of increasing task demands.

C. Sensorimotor Studies

Experiments involving volitional movement of finger and thumb have been carried out and the results used to interpret the accuracy of MEG (see the attached paper). The neuronal clusters associated with initiating fine motor functions as well as clusters involved with the somatosensory function of receiving information on muscle position are known to be quite closely spaced, on the order of 1 mm. The experiments to resolve these neuronal groups were carried out by having a subject move either the index finger or a thumb while recording the MEG. This was done at the subject's own volition and not as a result of a cue. The experiments were performed with the use of an electromyogram electrode (EMG) on the muscle so that timing could be synchronized to actual motion. Data were taken for 2s preceding the movement and for 0.5s after the movement. With MEG techniques it was possible to observe and map the readiness field, which preceded the actual motor signal precipitating movement. This readiness field starts about 1s before the actual commitment to move and originates in an area of the brain separate from the motor areas. Also, preceding the motor signal are the fields from the premotor area. The motor signal is observed immediately prior to EMG onset. Following movement onset, the somatosensory feedback response occurs.

A statistical analysis of the results of the motor experiments show the two sources can be distinguished, indicating the power of the MEG technique. Based on this result it is possible to consider a variety of applications for this MEG technique relative to performance evaluation. For example, it may be possible to monitor changes in premotor activities as a subject learns a manual task. It is known from monkey studies that the number of neurons used in a

task changes as the task is done more frequently; i.e., there is a focusing effect with training. Such an effect might be utilized to examine which type of training is most efficient at producing appropriate neurophysiological changes based on MEG measurements.

Another role of the motor response studies is their place in visual-motor and auditory-motor composite tasks. Experiments of this type, now under way, make use of visual cues to signal manual responses. The resulting motor field responses are measured to characterize both the influence of the stimuli and the effects of learning the visual-motor task on the actual brain information processing. Finally, the motor experiments and the measurements associated with brain produced fields may be of considerable value in future applications of man-machine interfaces. In these potential applications, the direct readout of volitionally produced magnetic fields associated with desired movements might be used to interface with machines.

D. Technological Issues

1. Hardware Developments

To obtain high-resolution ($\leq$ 2 mm) magnetic source localization in the human brain, it is necessary to know 1) precisely where the detectors are situated and 2) what the source characteristics are. The first of these two problems involves developing an instrument whose position is well specified relative to the center of the head. This instrument must also interact with the sensors in a manner that is uniquely dependent upon their relative locations.

To solve these problems, we have taken a straightforward approach, in which three sets of magnetic loop dipoles are placed 90° apart on a headband.

Each set contains three perpendicular, 2 mm diameter coils calibrated to produce equal strength magnetic moments. These nine dipoles will set up magnetic fields that differ at each point in space by virtue of their orientations and positions on the headband. The sensor array of seven gradiometers detects the fields produced by the dipoles, each of which is pulsed sequentially. The 63 readings should be more than adequate to specify both the location and the orientation of the gradiometer array relative to the head-centered coordinate system.

The position of the head center is specified by anatomical landmarks. A 3-D digitizer, already operational, shows these physical features, determines the head cartesian coordinate system, and calculates the locations of the dipole sets in this reference frame. This system is based on an optical system which projects a plane of light. The contour arising from the intersection of this light plane with the surface of the head is detected by an off-angle video camera. Given this information, the program for obtaining the sensor position and orientation involves only six variables plus the nine dipole angles as unknowns. These will be determined by applying a least squares routine which is being developed.

The second problem, namely the source characterization, is a very complicated one to analyze in detail. It is well established that neural activity involves intracellular current flow. To this extent, the magnetic signals are due primarily to short (~1 mm long) current sources whether these are simple dipoles, current sheets, quadrupoles, or even more complicated sources, has not been established for the general case. An adequate first order approximation can be obtained in many situations by assuming a linear

dipole moment. Even here, however, the return current paths needed to close the circuit are poorly defined. These may be of importance when the dipoles are deep in the brain or when they are radially oriented.

In order to establish the effects of the complicated brain electrical activity, two experimental approaches are being pursued. First, a five coil gradiometer is being tested to establish its ability to determine all three components of a magnetic field. This will make it possible to detect radial as well as tangetial fields and should provide a means for separating the intracellular dipole from the return current sources. Second, two simple dipole forms with cylindrically symmetric return paths have been fabricated. These test models will provide valuable information on the nature of the total magnetic fields. Based upon the results, more sophisticated experiments will be performed to simulate the effects of current sources in the nonhomogeneous and nonsymmetric environments that exist in the brain.

2. Software Developments

Computer software development for the MEG program continues to involve substantial effort. The MEG results are complex. Large arrays of data must be reduced to meaningful results in a short period of time if the goal of dealing with a large number of subjects is to be obtained. Additionally, since complex paradigms to test cognitive and performance abilities are being developed, they require complex data acquisition and stimuli software. Of extreme importance for the quality of the results are signal processing and correlation routines, which can considerably enhance the signal-to-noise of the data. Finally, the presentation graphics is important if the results are to be easily interpreted and understood, especially in future field applications.

The stimulus presentation and data analysis routines have evolved to utilize large number (32) of stimuli of complex types. This may involve both complex patterns, words, sentences, or sequences. Stimuli may be presented both visually or by sound. They are all time-locked to the main computer which keeps track of the stimuli and synchronizes the resulting digitized data to the stimulus presentation. Small dedicated computers are used for stimulus generation and these communicate with the main data acquisition computer. Depending on the experimental paradigm, stimuli rates of from four or more per second to one every few seconds are possible. These rates cover the entire range of expected stimuli for the higher-order cognitive paradigms considered.

A variety of signal processing and data analysis software routines have been developed to improve the quality of the data. In order to eliminate artifacts introduced by external stimuli or other environmental parameters, adaptive digital filters have been designed and are routinely used in the treatment of the data. The adaptive filter design has proved to be sufficiently successful to warrant hardware design for faster analysis. A noted improvement in the quality of interpretation of data has been achieved by using the method of Singular Value Decomposition (SVD) to extract individual components from the data (manuscript in preparation). This technique has resulted in an increase of 2 to 4 in the signal-to-noise ratio when determining source locations in the brain or establishing that different components arise from different sources. The development of this technique represents the first time it has been applied to MEG data and is a major step forward in understanding the complex waveforms observed in the MEG experiments. This result, coupled with new contour mapping algorithms, has produced significant

improvement in the representation of results (see paper by Aine et al.).

A major goal in the MEG program has been to develop techniques that can be used quickly and efficiently on a large number of personnel. For this reason it is important to be able to characterize the desired mental attribute with as few stimuli as possible. This not only increases screening efficiency but also reduces habituation problems and allows more complex tasks to be presented to the subject. A major step in this direction has been achieved by the development of an adaptive linear minimum mean square estimation technique which makes maximum use of the sensor array to examine correlations among the sensors. This technique has shown that in some circumstances it is possible to extract meaningful evoked responses from single-pass data by correlating data from all sensors in the array (see Fig. 8). In the worst case, considerable improvement of the data can be seen when correlations are utilized to improve the signal-to- background noise ratio. As sensor array sizes increase, the value of this technique will increase directly as the square root of the number of sensors. This new development thus represents a major step in the goal of developing a system capable of quickly assessing personnel capabilities using the least amount of machine time and the minimum number of test stimuli.

All of the above developments in software result in an imporvement in the imaging and diagnostic capabilities for MEG. To fully utilize these improvements, an adequate display system for the results must be available. For this purpose, considerable effort has been placed on graphical displays of the results. This effort ranges from simple displays of contour maps of the observed magnetic field lines to very sophisticated 3-D displays of the subject's full head profile with superimposed color displays of the magnetic

fields. The latter may be viewed as a movie in which the head can be rotated to any position and the field patterns are shown appearing and disappearing as a function of time following a visual or auditory stimulus. Addiitonally, when MRI scans are available for the subject, these can be digitized to show anatomical structures within the head. Actual neural sources, as determined from MEG, may be superimposed.

As this section demonstrates, software is an important component of the MEG program and parallels the development of the new cognitive paradigms. It is essential for a fully functional MEG unit to be used in the field for personnel evaluation.

III. Proposed Studies

Recently a major collaboration has been formed with a group of prominent cognitive psychologists. This has been accomplished with the assistance of ARI and in particular, Dr. George Lawrence. This group consists of Dr. Michael Gazzaniga, Dr. Stephen Kosslyn of Harvard University, Dr. Emilio Bizzi of MIT and Dr. Steven Hillyard of University of California. Drs. Gazzaniga, Kosslyn, and Hillyard have visited the LANL laboratory and all expressed satisfaction with the scientific quality of the work being carried out by the MEG group. Several proposals have now originated from this group and have been considered for the program. All of these experiments have been evaluated for their feasibility using MEG technology as well as for their scientific importance and relevance to the goals of the Army. It was decided that the most important experimental directions at this time were suggested by Dr. Steven Hillyard and by Dr. Kosslyn. Dr. Hillyard advocated further studies of selective attention and Dr. Kosslyn proposed studies of categorical vs coordinate spatial

representation. To provide the most expeditious route for implementing Kosslyn's experiment, which represents an entirely new direction of research, Dr. Marta Oakley was added to the MEG staff.

A. Selective Attention

As suggested by Dr. Hillyard, we propose to extend our studies of selective auditory and visual attention. Because ERFs and ERPs provide measures of selective processing in the absence of overt motor responses, it is possible to characterize an individual's attention capabilities by evaluating the onset, magnitude, and duration of processing various stimulus attributes. To further explore the limits of the attentional mechanism, we will modify our current experimental protocols (both visual and auditory) to present stimuli in much more rapid succession. Such modifications will have the effect of increasing the task load on the subject and forcing the attentional mechanism to be engaged more quickly. By comparing our results from the faster presentation rate with those at the slower rates, it will be possible to determine whether different strategies are recruited under more difficult environmental conditions. We are interested in determining whether hypothesized changes in strategies (as reflected by ERF distributions) is related to a subjects ability to selectively allocate attention to competing classes of stimuli.

B. Categorical vs Coordinate-Spatial Representation

This research will have three phases. The first is a rather small-scale study designed to discover whether the approach is worth pursuing. This study is intended to examine two issues that are at the root of the proposed differences in applications. The second and third phases are a larger-scale

effort to validate a brain-based measure of individual differences in the ability to use and remember metric spatial information.

1. Phase I

a. Summary and Overview

Four subjects will be tested initially in order to learn how to use the individual differences that MEG measures. Two issues will be examined in this study. First, we will examine whether categorical spatial relations (e.g., "left of," "above," "connected to") tend to be processed in the left hemisphere more than in the right and vice versa for coordinate spatial locations (i.e., actual metric distance from an origin). Second, we will examine whether the parietal lobe is involved in representing spatial relations in general, or whether it is used only in representing spatial relations among separate objects in a scene (and not relations among parts of a single object). These two issues interact, in that it may be that the left parietal lobe is involved whenever categorical relations are used (among objects in a scene or among parts of a single object), but the right parietal lobe is involved only when objects in a scene are represented. These issues are of interest because they lead to the characterization of a "brain signature" that may reflect individual differences in the ability to use and remember metric spatial information.

b. Tasks and Stimuli

Two judgment tasks, categorical and coordinate, will be employed. Pairs of stimuli will be presented either in the left or right visual fields (in order to differentially activate the two cerebral hemispheres). Each stimulus pair will consist of two symbols "+" and "x". The spatial arrangement of the two symbols will vary along the two judgment dimensions: (1) categorical, i.e.,

"left of" or "right of" and (b) coordinate, i.e., the distance between the two symbols will vary from about 0.6 to 1.8 cm in four equal increments.

C. Preliminary Results

It is of interest to monitor activity in both parietal lobes (particularly in the region of area 7a), and in both posterior, inferior temporal lobes. It is also of interest simply to know where the strongest responses occur in each hemisphere in each type of task.

The outcome of Phase I will be information about what sorts of stimuli to use and where to monitor to obtain the best responses to them. This initial study will reduce the effort of recording from the larger number of subjects in Phase II.

Phase I of this project has been under way since February 1988. To date, behavioral and physiological measures (ERF and ERP) have been obtained from five subjects (four males, one female; ages 17-43).

The reaction time data are consistent with Kosslyn's hypothesis. In the coordinate judgment task the LVF (right hemisphere) yields shorter RTs (809.7 ms) than the RVF (left hemisphere, 838.3 ms), and in the categorical task the RVF (left hemisphere) yields shorter RTs (739.8 ms) than the LVF (right hemisphere, 763.2 ms).

MEG results also indicate spatial and temporal differences between the two tasks. The temporal changes in dipolar structure mirrored the RT pattern. For example, a dipole was activated sooner in the left hemisphere than in the right when the subject performed a categorical task. These temporal effects had an onset latency around 400 ms.

The spatial differences are of three types. (1) The hemisphere which had an advantage in making one type of judgment produced a dipolar source of relatively small magnitude which was not present for the other task. For example, in some subjects there was a right hemisphere source to the coordinate task that was absent in the categorical task. (2) In other subjects, the distribution across tasks was identical in a given hemisphere, but the magnitude of the source followed the predicted hemispheric specialization. (3) There were two dipole sources in one hemisphere which had a different origin according to the task. These differences had an onset latency of about 400 ms and a duration of about 50 ms.

Comparison of ERF and ERP results indicate that the ERPs are insensitive to the subtle changes observed in the MEG recordings.

In summary, the pilot data seem to support the hypothesis set forth by Kosslyn and indicate that the MEG technique is the most sensitive methodological tool available to us at the present time for detecting the hemispheric differences produced by mental activity.

2. Phase II

a. Summary and Overview

In Phase II, at least 24 subjects will be tested, and various MEG measures will be correlated with scores on spatial abilities and nonspatial abilities tests (which should not correlate with the MEG measures). The MEG measures and test scores will be used to predict real-world navigation and visual memory abilities.

b. Tests

The spatial abilities tests will include the Flaggs test, Ravan's

Progressive Matrices and Cube Folding, and Dots-and Arrows (a new test that should tap metric spatial ability per se). The nonspatial tests will include digit span, mathematics ability, and vocabulary tests. If the MEG measures are significantly correlated with any of the nonspatial measures, these scores will be used in multiple regression analyses to partial out the relation between these variables and the MEG measures, allowing us to consider the relation between the spatial abilities tests per se and the MEG measures.

c. Dependent Measures

The primary goal of the second phase of the research is to discover a brain marker that will reflect how well a person can form coordinate spatial representations. A number of measures will be evaluated, with approximately 12 being derived from the MEG data. For each of three different components of the evoked response fields recorded from two locations (the parietal lobes or temporal lobes), we will compute left hemisphere/right hemisphere (LH/RH) for categorical trials, LH/RH for coordinate trialls, and (coordinate/categorical for LH)/(coordinate/categorial for RH).

d. Ecological Validity

The final stages of the research involve examining the relationship between the MEG measures (and correlated tests) and performance in real-world tasks. The two tasks to be examined here are memory for spatial locations of objects in a scene and navigation ability. The subject will be presented with two tasks, each assessing different types of visuo-spatial memory. The first one will test incidental visual memory. The task will involve bringing a subject into a unfamiliar room and after a brief exposure, he will be asked to draw the spatial relationship, including distances, between objects located in

that room. The second task will test the subject's intentional visual memory. Again the person will be led to an unfamiliar room, but this time will be instructed to remember the contents and spatial arrangements of objects for subsequent reproduction.

It is expected that the "brain signature" will predict the individual's behaivoral response.

3. Phase II

The aim of this phase is to incorporate the findings of the above-stated experiment (visual-spatial memory) into a broader study to investigate perceptual accuracy. In other words, why are some individuals accurate in predicting metric distance or in making categorical judgments while others are not? Further, can an easily learned strategy improve those skills?

Imagery is the best known mnemonic device for improving memory. It is often assumed that imagery involves some type of "brain reorganization" such that certain brain areas are primed and ready to analyze the incoming sensory signal even before the stimulus is presented. It is this type of reorganization that may lead to more accurate performance.

Two groups of subjects, "good" and "poor" imagers, would be selected based on a Mental Rotation Task.

1. The two groups will be tested in the categorical vs coordinate judgment task and their brain responses will be correlated with their imagery ability.

2. If significant differences in brain activity are found between imagers and nonimagers, the brain areas which seem to be involved will be localized.

3. The poor imagers will be trained in improving their imagery. Those who master this task will be retested several months later to establish whether imagery improved their ability in the coordinate or categorical judgment tasks and whether different brain areas are activated during this task.

C. Monitoring Stress Using MEG

As described in Sec. II.B, selective attention to auditory stimuli produces specific changes in event-related brain activity. This effect can be observed in a selective dichotic listening task in which subjects are instructed to detect occasional pitch changes in a stimulus sequence delivered to one ear while ignoring similar auditory input to the other ear. The attention effect appears as a broad offset (Ndm) which differentiates between responses to the attended stimulus and responses to the same stimulus when it is ignored. By modifying this paradigm so that all tones are presented to each ear, the task will be much more difficult. We are interested in determining the impact of increasing task load on the attention-related brain activity (Ndm) as a model for examining the effect of increasing stress levels on processing resources and ultimately on performance.

In this protocol, there will be eight effective stimuli which vary along three dimensions; two of which define the attended channel (ear and pitch) while the third (duration) differentiates the targets from standards. Channel cues will be presented equiprobably ($p = 0.2$) whereas targets in each channel will be one fifth as numerous as ($p = 0.05$). Specifically, subjects will listen to randomized sequences of tones which vary in pitch (1.5 kHz and 2 kHz) location (left ear and right ear) and duration (51 ms standards, 102 ms targets). Thus, tones could either be standards or targets at frequency of 1.5

kHz or 2 kHz occurring in either right or left ear. Stimuli will be presented at 50 dB SPL with interstimulus intervals varying at random between 500 to 800 ms. Attention and accuracy will be monitored by recording RTs to target stimuli.

If the MEG response is a good predictor of tolerance for stress, it should be possible to screen subjects to determine the relative ability for individuals to tolerate increasing sensory loads. A longer-term application would be the development of MEG monitoring procedures so that individuals in critical jobs might be tested daily to evaluate their tolerance for stress.

IV. Summary of Progress and Consideration of Final MEG Products

The experimental results of the LANL MEG project to date have been a systematic study of sensory processing ranging from spatial localization of simple stimuli to cognitive processes involving selective attention. These experiments, coupled with technological developments, have placed the MEG laboratory on a firm scientific footing for examining higher cognitive processes related to performance evaluation in both training procedures and selection of appropriate personnel. Moreover, the recent advances in technology have directly addressed the problems associated with processing of large numbers of individuals rapidly.

The primary goal of this project is to utilize MEG measures of brain activity to enhance personnel selection and training procedures. The general concept underlying this approach is that unique "brain signatures" may reflect specific (vocational) abilities. As mentioned previously, the rationale for pursuing the identification and characterization of neural correlates of specific cognitive functions rests on the assumption that these measures

provide more information than simple RT measures about how individuals process certain types of information. This method allows for the examination of neural activity between the stimulus and the response during different behavioral tasks. It may be, for example, that the amplitude, latency, or location of a neural generator of a component of the MEG waveform (e.g., P100) is a better predictor than RTs of the spatial ability under scrutiny.

We have approached this problem area systematically by first identifying simple stimulus evoked responses and then by examining the role of selective attention on these processes. We are now in the position to examine possible neural correlates of higher cognitive functions involving spatial abilities (e.g., metric vs coordinate judgments). Once these neural correlates have been identified, these results will be correlated with other pencil/paper tests on both verbal and spatial tasks to determine whether the neural measures really do provide a measure of the spatial ability of interest (construct validity).

There are two different directions in which one could use these neural correlates of behavior. First, these correlates could be used in the development of tests--that is, we can take a specific real-life situation and correlate performance in this situation with the MEG and other pencil/paper measures. An an example, we could obtain measures of performance on a task which most closely approximates a real-life situation requiring spatial ability (e.g., having subjects walk into a room for a short duration and then having them recall the room environment from memory). A discriminant analysis would then be performed with the aim of predicting performance on the real-life task. By adding MEG measures, RT measures, and other measures of spatial ability (pencil/paper tests) to this multiple regression equation, we could assess

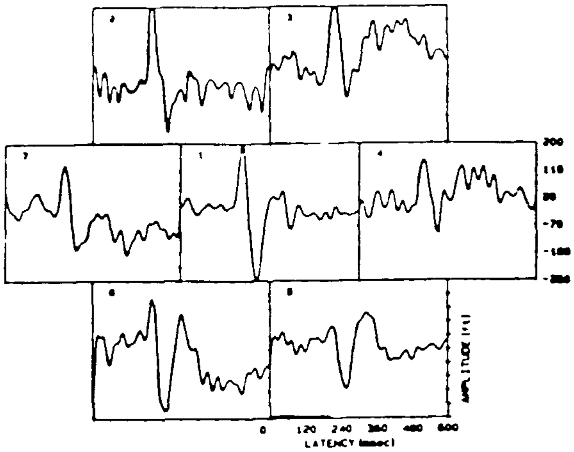
whether the MEG measure best predicts performance on spatial memory tasks. Alternatively, it is possible that the MEG results would not be the best predictor but rather contribute significantly (in percent of variance accounted for) when used in conjunction with other tests. In either case, the final step would involve the construction of a paper/pencil test that would best correlate with either the MEG results alone or in combination with other tests. This step is considered important since it could be infeasible to obtain MEG measures on all recruits.

Second, we could use the MEG correlates in training recruits to have specific skills. For example, it is probable that particular strategies used in a task elicit an identifiable pattern of brain activity. By characterizing the pattern of activity in individuals who perform well on the task of interest, one could then develop a type of neural standard for others to strive toward during training.

1. 7-SENSOR ARRAY

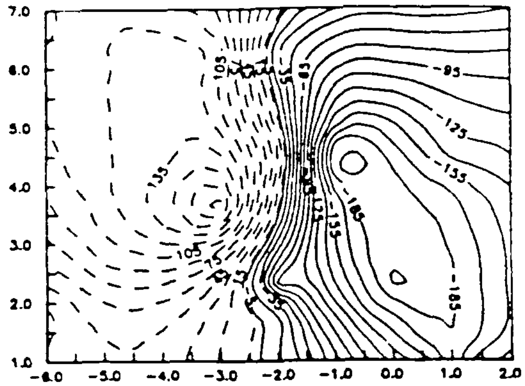
2. CONTOUR PLOT

Sinusoidal Grating In Right Visual Field



Left Hemisphere Recordings

Field Distribution -- 100 msec



Left Hemisphere

Inion

3. LEAST SQUARES CODE

PSI=-5.44 PHI=161 THETA=66.5 DEPTH=3.09 cm MOMENT=18.7

4. MAGNETIC RESONANCE IMAGING (MRI)

Midsagittal View

Horizontal View

Figure 1.

STIMULUS: 1 cpd GRATING IN LOWER RIGHT FIELD

LEAST SQUARES SOLUTION:

PSI= -14.0 PHI= 158.0 THETA= 59.4 DEPTH= 2.36 MOMENT= 10.6

CONTOUR PLOTS--100 MSEC (poststimulus)

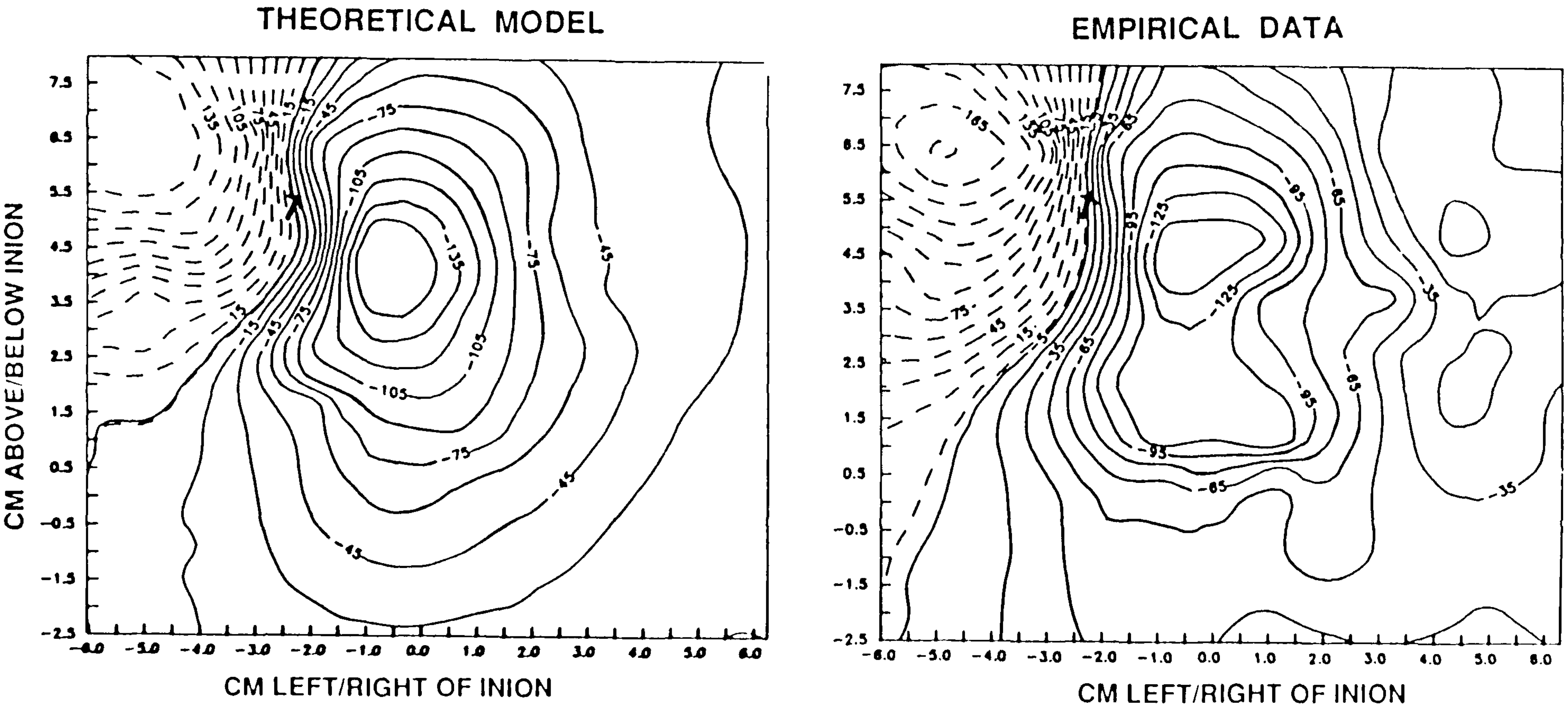


Figure 2.

EFFECT OF FIELD OF STIMULATION

(1 CPD SINUSOIDAL GRATING -- 110 MSEC)

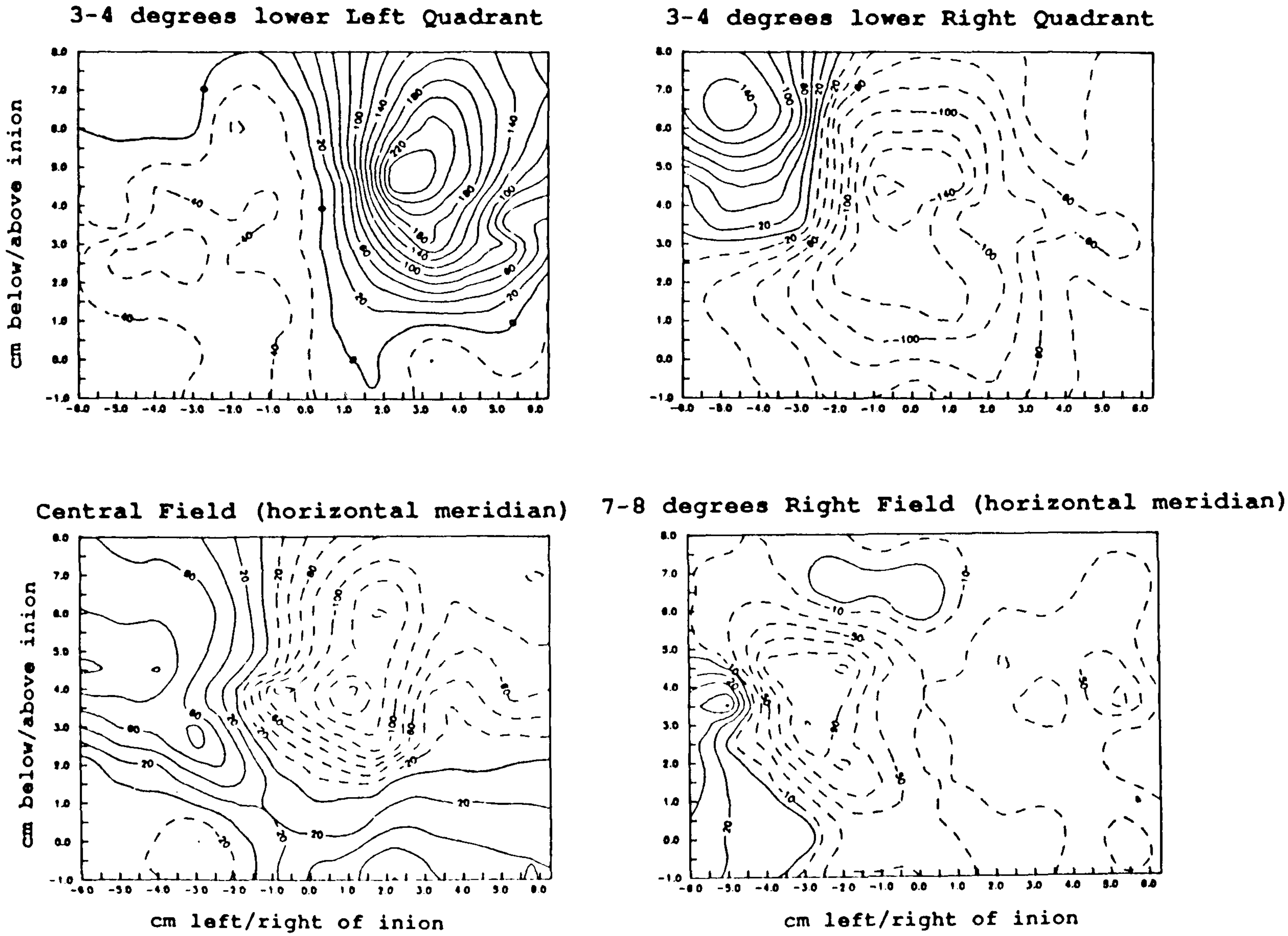


Figure 3.

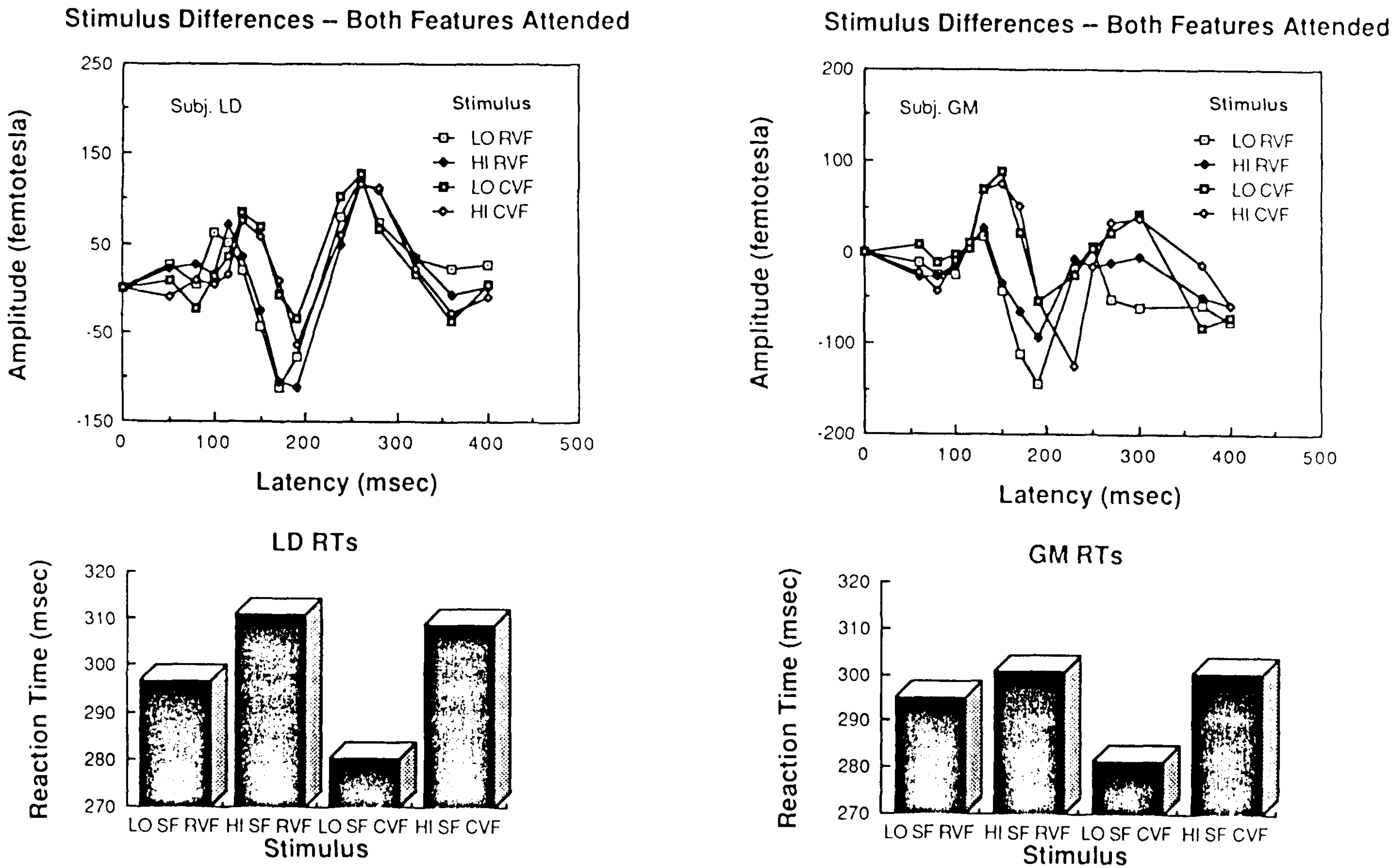

Stimulus Differences -- Both Features Attended
Subj. LD
Stimulus
LO RVF
HI RVF
LO CVF
HI CVF
Amplitude (femtotesla)
250
150
50
-50
-150
0
100
200
300
400
500
Latency (msec)
Stimulus Differences -- Both Features Attended
Subj. GM
Stimulus
LO RVF
HI RVF
LO CVF
HI CVF
Amplitude (femtotesla)
200
100
0
-100
-200
0
100
200
300
400
500
Latency (msec)
LD RTs
Reaction Time (msec)
320
310
300
290
280
270
LO SF RVF
HI SF RVF
LO SF CVF
HI SF CVF
Stimulus
GM RTs
Reaction Time (msec)
320
310
300
290
280
270
LO SF RVF
HI SF RVF
LO SF CVF
HI SF CVF
Stimulus

Figure 4.

EFFECTS OF ATTENDING A 1 CPD GRATING IN RVF

(THE P110 AND P300 COMPONENTS)

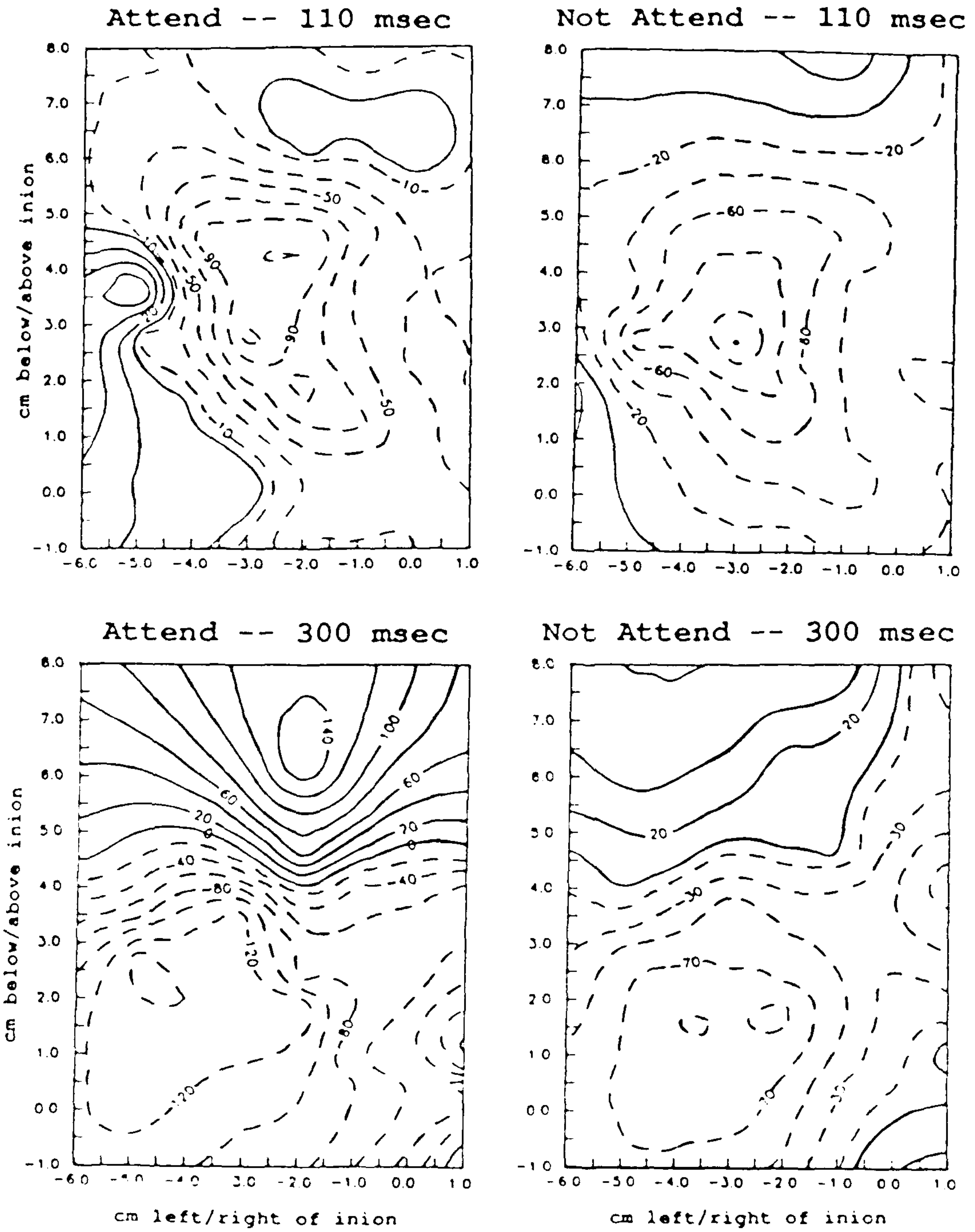


Figure 5.

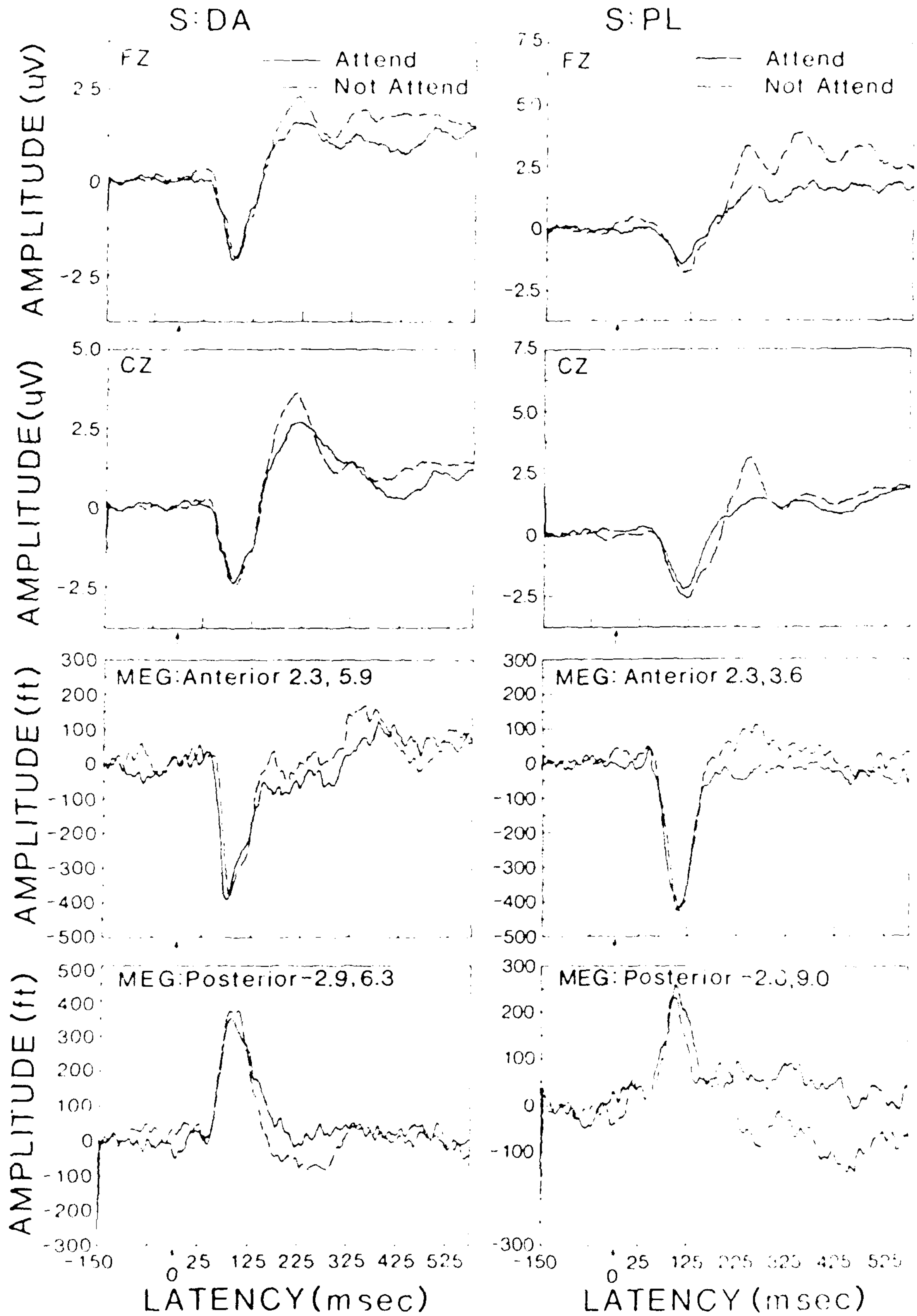

S:DA
S:PL
FZ
Attend
Not Attend
CZ
MEG:Anterior 2.3, 5.9
MEG: Anterior 2.3,3.6
MEG:Posterior-2.9,6.3
AMPLITUDE (uV)
AMPLITUDE (ft)
LATENCY (msec)

Figure 6.

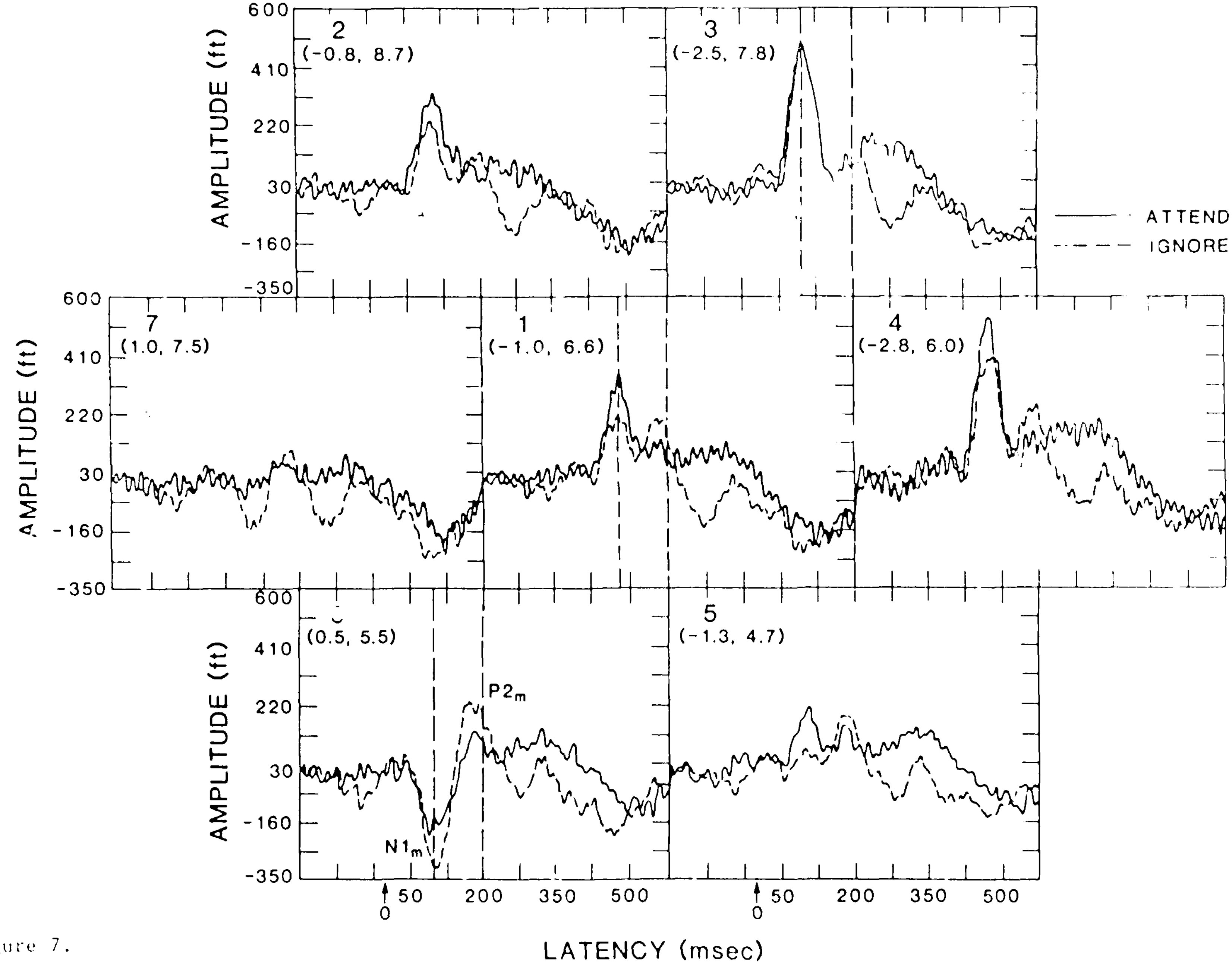

2
(-0.8, 8.7)
3
(-2.5, 7.8)
7
(1.0, 7.5)
1
(-1.0, 6.6)
4
(-2.8, 6.0)
(0.5, 5.5)
5
(-1.3, 4.7)
P2m
N1m
ATTEND
IGNORE
AMPLITUDE (ft)
600
410
220
30
-160
-350
0
50
200
350
500
LATENCY (msec)

Figure 7.

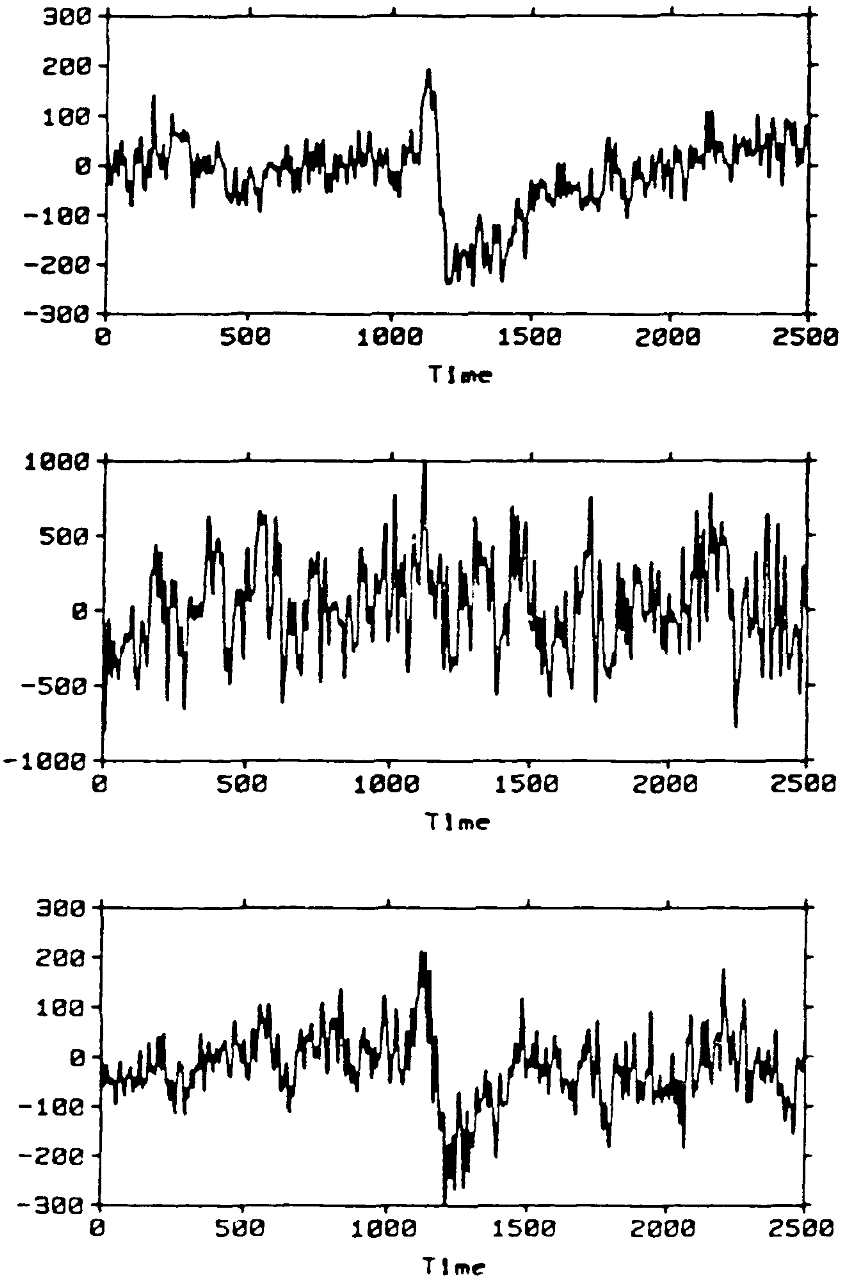


Figure 8. *Auditory evoked response to stimuli at 1000 ms. The top sequence is the average of 50 trials, the middle a single trial, and the bottom the enhanced single trial. (The amplitudes are in fT and the times are in ms.)*